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Water hyacinth (Eichhornia crassipes) for organic contaminants removal in water – A review

Farah Amalina[a], Abdul Syukor Abd Razak[a], Santhana Krishnan[b], A.W. Zularisam[a], Mohd Nasrullah[a,*]

[a] Faculty of Civil Engineering Technology, Universiti Malaysia Pahang (UMP), Lebuhraya Tun Razak, Gambang, Kuantan, Pahang 26300, Malaysia
[b] PSU Energy Systems Research Institute, Department of Environmental Engineering, Faculty of Engineering, Prince of Songkla University, Hat Yai, Songkhla 90110, Thailand

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ABSTRACT

Water hyacinth (WH) is well-known as an invasive species that threatens aquatic biodiversity worldwide. Manual or physical removal of this substance from water is necessary to avoid secondary water pollution caused using chemically synthesized herbicides by its control, resulting in organic waste generation. Researchers recently recommended, among other things, this waste might be converted into adsorbents that can be used for the remediation of water resources, as well as other applications. This is critically important since clean water is still required in all aspects of life, regardless of its quality. The remediation approaches presented for the treatment of water supplies through the remediation of organic contaminants utilizing WH are discussed in this study. Research into the use of WH for phytoremediation and the removal of organic contaminants has been conducted in detail. It can be seen from this review that the overview of various works was more concerned with the removal of organic dyes from water than with any other topic. A study of the underlying mechanisms in the adsorption processes is presented in this context. Towards the end of the paper, it is suggested that future research into the use of WH to remediate water resources will aid in the water resource environmental management.

1. Introduction

The spread and proliferation of WH, formally designated as Eichhornia crassipes, in nutrient-rich bodies of water has become a global concern. According to published data, the free-floating perennial hydrophyte WH spreads fast across the entire continent and globe (Hashem et al., 2020). Fig. 1 depicts the distribution of this invasive species based on the records presented by the Centre for Agriculture and Bioscience International (CABI). In Thailand, the growth of WH in numerous major streams surged to 5.6 million tonnes monthly (Jirawattanasomkul et al., 2021). WH plants grow to extremely dense volumes exceeding 60 kg m^{-2}, severely blocking waterbodies (Gaurav et al., 2020). Their maximum height is 1 m, albeit a 40 cm height is most frequent (Liu et al., 2018). Due to the leafy plant's size, WH absorbs sunlight, depriving marine life of environmental supplies notable oxygen from the atmosphere. Furthermore, the presence of WH in environmental biodiversity has a detrimental impact on the tourism industries in certain nations, where visitors visit reservoirs and dams for recreational and leisure purposes (Ayanda et al., 2020). Numerous methods are used to remove WH from water bodies to address these issues. In contrast to herbicide control, mechanical removal is widely used, bringing secondary water pollution into waterways via chemical contamination caused by herbicides (Li et al., 2021).

Owing to the abundance of WH extracted from water, practical applications of WH were explored. Fig. 2 illustrates and summarises several of the diverse applications of WH in the removal of water contaminations. Since the 1980′s, WH has been used to combat water pollution (Liu et al., 2020). WH biomass can remove metals and organics in water (Madikizela, 2021; Nyamunda et al., 2019). Recent attention has been drawn to its stringent uses for removing organic dyes (Liu et al., 2020; Salahuddin et al., 2021; Sharma et al., 2021). While some researchers preferred to use the native form of WH for adsorption studies, others preferred to use modified WH-based adsorbents (Chen et al., 2019; Sahoo et al., 2019). According to some researchers, two weeks is sufficient for the effective treatment of domestic water with WH (Huang et al., 2020). Subsequently, numerous reports have been published in the field critically examining the potential of employing WH in phytoremediation (Milke et al., 2020Zhou et al., 2020; Ayanda et al., 2020). Among the reviews presented, Ayanda et al. (2020) focused on the effectiveness of WH in reducing organic and inorganic contaminants in wastewater. In contrast, another analysis assessed the efficacy and economics of using WH as an adsorbent for textile treatment effluent

* Corresponding author.
E-mail address: mnasrul@ump.edu.my (M. Nasrullah).

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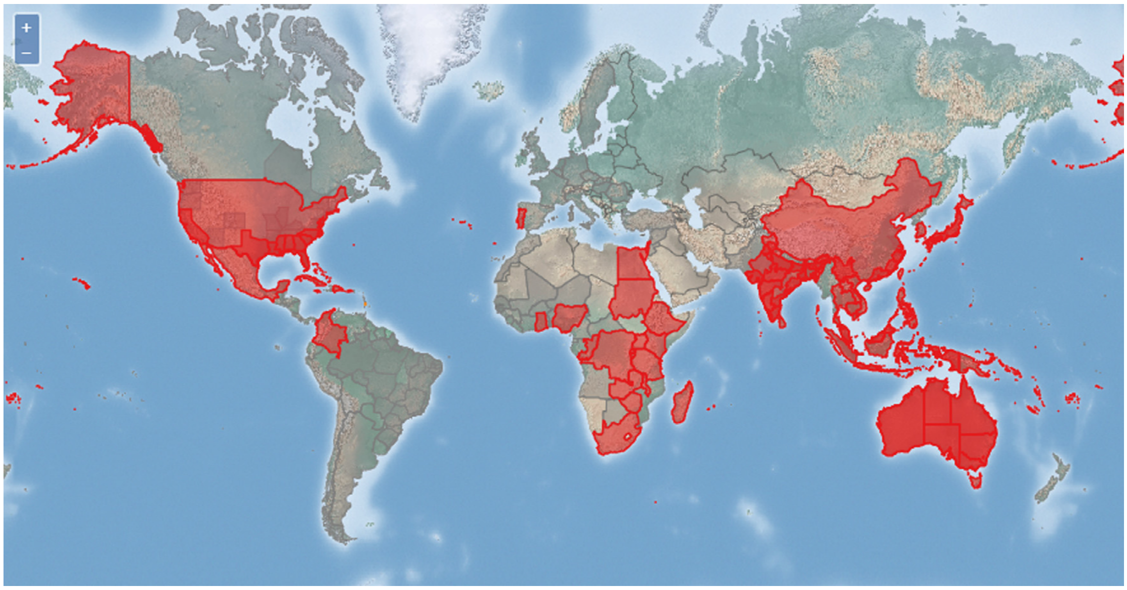

Fig. 1. Distribution of WH species across the continent (CABI, 2022).

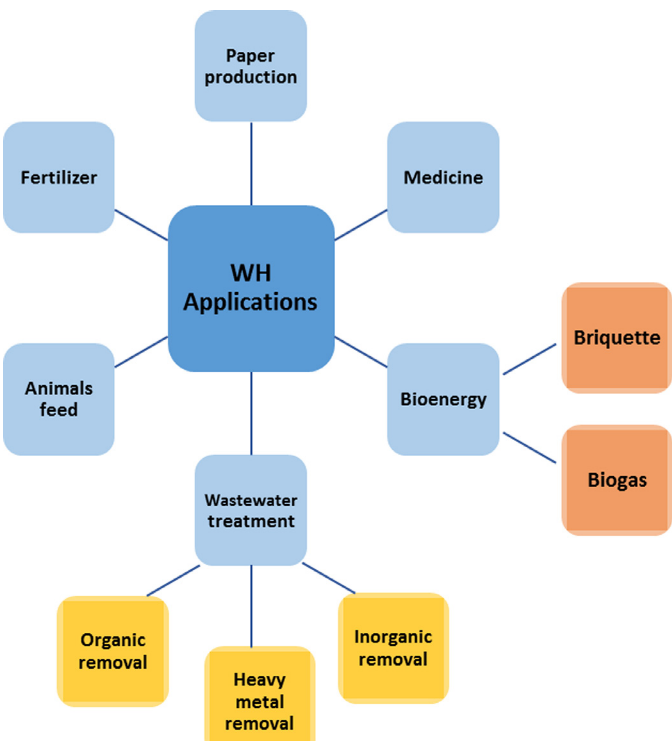

Fig. 2. WH applications.

(Yao et al., 2019). Elsewhere in the article, the emphasis was primarily on the potential for phytoremediation with WH to eliminate heavy metals, organic and inorganic contaminants from water (Huang et al., 2020).

A detailed discussion reflects the novelty of the present work on WH. The characteristics of WH and biochar from its biomass are also discussed in detail. In-depth elaboration on the removal of organic pollutants in water and applications of WH has been covered in this work. The variables that affect the adsorption process, such as pH, initial concentration of the dye, contact time and temperature, have been discussed in detail. The dye adsorption from WH biomass using roots, leaves, and stems is also discussed in this paper. One of the essential products in the current time that be applicable for various purposes like biochar production. In this paper, WH has been found as one of the prospective sources for fulfilling sustainable waste management as it can sustain itself in diverse social, economic, and environmental conditions.

Like previously published studies, the primary objective is to contribute a current comprehensive assessment of the use of WH to remediate organic contaminants from waterways. The literature reports on organic removal strategies such as adsorptive technologies and plant adsorption from contaminated freshwater. This research aims at a critical examination of the mechanisms influencing pollution removal. These are vital and relevant factors to consider while organising future research initiatives.

2. WH characteristics

WH is thoroughly discussed as biomass in a recently published research study (Gaurav et al., 2020). The capability of WH to absorb toxic waste from the water is a result of its unique properties compared to other aquatic species. WH is made of structural carbohydrates such as lignin, crystalline cellulose, and hemicellulose polymer (Zhang et al., 2020). As a result, the surface of WH contains critical functional groups, especially carboxyl, hydroxyl, and carbonyl, which act as a catalyst for the adsorption of water contaminants onto plant-based adsorbents (Brown et al., 2020). The roots of WH contain functional groups —PO_4, C=O, and C—H (Milke et al., 2020). The composition of WH fibres includes a significant amount of cellulose in the form of hemicellulose (33%), cellulose (25%), as well as lignin (10%) (Salahuddin et al., 2021). These WH features urge scientists to study the invasive species' applicability for water restoration. Several research-based experiments have also been done using cellulose from WH to eliminate water contaminants (Emam et al., 2020; Salahuddin et al., 2021). This is mainly because this aquatic plant's cellulose backbone contains multiple hydroxyl groups (Singh and Chandra, 2019). These hydroxyl groups are the primary determinants of adsorption, chemically tuned to facilitate generation.

WH is well-prominent for its porous structure, and scientists have explored carbonising the material to develop mesoporous carbon, producing higher active species (Zhang et al., 2020). WH-based adsorbents have a lesser surface area than synthetic-based adsorbents for adsorption uses. According to studies, the surface areas of WH's roots are between 4.5 and 5.8 m^2 g^{-1}, while the surface areas of its petioles are between

2.5 and 3.3 m^2 g^{-1} (Madikizela, 2021). Surprisingly, most WH-based adsorbents are generated from roots. Specific functional groups in plant biomass primarily determine their adsorption capacity. The surface area of WH-derived biochar was 50.5 m^2 g^{-1} in one experiment (Xu et al., 2020). In certain circumstances, the chemical treatment of WH is used to enhance the surface area and thus the adsorption process. This is a critical need, and adsorption was directly proportional to the specific surface area (Gwenzi et al., 2017).

3. WH organic contaminants removal from water

For many years, the need for efficient methods to eliminate these organic contaminants has been a challenge for ecologists and scientists. Various methods for organic contaminant removal from wastewater have been investigated and reported in the literature. These include froth flotation, precipitation, flocculation-coagulation, reverse osmosis, membrane filtration, photodegradation, electrochemical destruction, irradiation-ozonization, Zn-Ferrite inorganic catalyst-assisted photo Fenton degradation, adsorption using nanoparticles and adsorption using commercial grade activated charcoal (Bapat, 2020; Cuerda-Correa et al., 2020; Mamane et al., 2020).

Most contaminants are easily removable by the least expensive coagulation-flocculation process among the various treatment choices. However, there are constraints, particularly against the profoundly dissolvable, cationic and low sub-atomic direct colours such as Methylene Blue (Enaime et al., 2020; Samsami et al., 2020; Sonu et al., 2020). For the removal of persistent dyes after this treatment, advanced techniques like chemical oxidation or adsorption are required as most of these dyes are non-biodegradable (Chen et al., 2019; Pan et al., 2021; Zhu et al., 2022). So, to advance a conservative arrangement, the development of eco-friendly and cost-effective adsorbents has gained high importance as the expenses are much lower in comparison to the other advanced methods, including ion exchange, membrane filtration, ozonation, photochemical oxidation, sonolysis, and so forth (Awe et al., 2020; Talaiekhozani et al., 2021; Tkaczyk et al., 2020). Out of the methods listed above, adsorption with commercial grade activated charcoal has gained the most popularity in the textile industry due to its ease of handling. However, the high cost of activated charcoal makes the technique expensive, limiting its usefulness as an adsorbent (Bapat, 2020).

Therefore cost-efficient, viable and durable adsorbent substances for the treatment of dye wastewater need to be explored. In line with this, researchers have identified various efficient, low-cost, and natural alternatives for activated charcoal as an adsorbent. This includes WH biomass as a precursor for an alternative energy source that can be used efficiently due to its abundant availability at low cost, sustainability for waste management, economy, ecology, energy, and society (Gaurav et al., 2020).

3.1. Plant uptake of organic pollutants

The plant uptake of numerous organic contaminants from water using WH was comprehensively documented (Feng et al., 2021; Mahfooz et al., 2021; Mlunguza et al., 2020; Sharma et al., 2021; Yamkelani Mlunguza et al., 2020). This indicates that WH is usually to be a significant player in phytoremediation. Most organics uptake investigations have been accomplished in hydroponic systems (Yan et al., 2019,2019). Table 1 summarises the adsorption efficiency obtained for several chemical substances. As demonstrated in Table 1, 83.5% of antibiotic sulfadiazine at 1 mg L^{-1} was removed over 25 days of disclosure (Yan et al., 2019). According to similar research, sulfadiazine toxin in the water had no effect on the health or survival of WH, particularly indicated by chlorophyll concentration, chlorophyll fluorescence, and antioxidant enzymes assessment. Additionally, contradicting data has been presented for ciprofloxacin, showing that the colour of WH changes to white after 14 days of exposure owing to a fall in chlorophyll content and fluorescence characteristics of chlorophyll (Yan et al., 2019). Correspondingly, after approximately 17–20 days of exposure to WH in the aqueous dye solution, a decrease in stiffness was reported (Sharma et al., 2021). According to an investigation (Benkhaya et al., 2020), decolorization was between 79 and 90.8% for cationic dyes and 33.3 and 62.8% for anionic dyes. Another analysis revealed that 82.5% of chemical oxygen demand (COD), a proxy for the volume of organic substances in water systems, was lowered (Gopinath et al., 2021). Throughout the 1990′s, it was discovered that WH was extremely functional, removing COD from wastewater treatment plant discharge that had been stated to contain till 1000 mg L^{-1} (Madikizela, 2021). Diverse outcomes described in the literature could result from exposure time variations. Roots were found as the primary polluted absorbers in all cases (Yan et al., 2019, 2019). According to a recent analysis, pollutant uptake (in this case, pharmaceuticals) mainly occurs via roots, then transfers into aerial tissues such as stems and leaves (Madikizela et al., 2018).

Together in a new situation, it was discovered that WH obtained from surface water included pharmaceuticals (selective non-steroidal anti-inflammatory medications and antiretroviral drugs) that have been thought to be taken from polluted water by plants via their roots (Reza et al., 2020; Zhang et al., 2020; Zubair et al., 2021). This is just more proof that WH effectively eliminates contaminants from water, hence providing a potential option for phytoremediation. According to one investigation, WH roots contained substantially high dosages of the antiretroviral drugs studied, varying between 7.4 to 29.6 μg kg^{-1} (Mlunguza et al., 2020). In contrast, another report described the roots' uptake of non-steroidal anti-inflammatory drugs and subsequent translocation into other segments (Yamkelani Mlunguza et al., 2020). Thereby, contaminants absorbed by plants have been discovered throughout every part of the plant (roots, stems, and leaves) (Mlunguza et al., 2020; Reza et al., 2020; Yamkelani Mlunguza et al., 2020).

Research has established WH is an excellent plant species for removing contaminants from water in waterways (Jirawattanasomkul et al., 2021). Translocation ratios demonstrated WH is a booming plant capable of phytoremediation for all organophosphorus and organochlorine pesticides in a wetland ecosystem (Haziq et al., 2020). In another study, non-steroidal anti-inflammatory medication (ibuprofen) and caffeine were effectively removed (>80%) in a created wetland (Oginni et al., 2019). Scientific study has demonstrated WH can be implemented in wastewater treatment plants' waste stabilisation ponds to optimize pollutant control (Hoko and Toto, 2020). With an instance of organic waste removal from wastewater utilising WH, it was determined that two chained ponds were required for efficient remediation (Carolin et al., 2017). A study detected the highest content of organic compounds in plant roots on day 3 of disclosure and finally translocated into the stems, peaking on day 6 and reaching the maximum concentration on leaves on day 8 (Talaiekhozani et al., 2021). As a result, there is evidence of fast organic matter translocation from the roots to the leaves of WH via the stems.

3.2. Organic pollutants removal

3.2.1. WH as an adsorbent

At present, carbon-based materials produced by WH have been discovered to eliminate a large volume of organic contaminants in water sources. These organic substances comprise phenol (Talaiekhozani et al., 2021), sulfachloropyridazine (Wang et al., 2021) with additional sulfonamides (Liu et al., 2018), fluoroquinolones (Cuerda-Correa et al., 2020) and tetracycline (Tomczyk et al., 2020). In such a case, lignocellulosic fibres isolated from WH were employed to absorb volatile n-alkane hydrocarbons (Mahfooz et al., 2021). Conversely, findings revealed that the mineral acid and organic solvent modified WH root biomass had a better capacity for the sorption of volatile n-alkane hydrocarbons (Mahfooz et al., 2021). Based on the enthalpy of adsorption, the same study group concluded that the adsorption bond of volatile

Table 1
Organics removal by WH in water (hydroponic experiments).

Organic compound	Agent	Concentration (mg L^{-1})	Time (days)	Removal capacity (%)	Refs.
Mesotrione and fomesafen	Herbicides	100	14	96.7–98.2	Zhang et al. (2020)
Naphthalene	Polycyclic aromatic	13	9	100	Mahfooz et al. (2021)
Formaldehyde	Aldehyde	200	10	93	Benkhaya et al. (2020)
Sulfadiazine	Antibiotic	1	25	83.5	Yan et al. (2019)
Oxytetra-cycline hydrochloride, chlortetracycline hydrochloride and tetracycline hydrochloride	Antibiotics	15	20	>80	Yaashikaa et al. (2019, 2020)

polar solvents on WH root biomass is greater than the adsorption bond with preponderance lignocellulosic adsorbents were formerly examined (Santoso et al., 2020). Another research established that the pH substantially impacts the adsorbent's surface charge and the adsorbate's ionisation degree (Meko, 2021; Mishra et al., 2021; Zhou et al., 2019). This implies that the pH can be seen as a driving element of the adsorption process. This has been proven in the sorption of sulfachlorpyridazine and its variants utilizing the WH root powder. Extensive sorption occurs at low pH due to electrostatic contact, hydrogen bonding, and π-π interactions (Liu et al., 2018). The creation of structures must be acknowledged in stimulating the adsorption process alongside the pH modifications.

The sorption of tetracycline confirmed this onto WH roots (Selmi et al., 2018). For example, the researchers introduced Cu^{2+} in the adsorption media between pH 4 and 6, which generated a strong metal bridge across the root surface and tetracycline molecule. They therefore improved the adsorption rate (Bedia et al., 2018). It emphasizes the necessity of chemical enhancement of WH adsorbents to strengthen a surface to absorb organic molecules from water efficiently.

3.2.2. Chemically treated WH adsorbents: applications

WH was demonstrated as a unique adsorbent for organic and inorganic contaminants (Mahfooz et al., 2021). WH treated with phosphoric acid is an efficient adsorbent for organic and inorganic contaminants (Feng et al., 2021). Nevertheless, surface modifications are intended to enhance the properties. For instance, the inclusion of Fe_3O_4 magnetic particles and modification by 1H, 1H, 2H, 2H-perfluorooctyltriethoxysilane increased its magnetic and mechanical properties (Sun et al., 2020). The resultant adsorbent exhibited a large porosity, a lower skeletal density, and excellent magnetic, hydrophobic and lipophilic properties, indicating that it was an ideal substance for oil adsorption, with an adsorption efficiency of approximately 140.90 g g^{-1} (Sun et al., 2020). Magnetic particles increased the adsorbent's isolation from water, increasing its reusability. A magnetic hybrid material containing WH was reused six times to reduce inorganic and organic contaminants from the aqueous phase, achieving 70–100% removal for ibuprofen (Lima et al., 2020). Additionally, a magnetic carbon composite adsorbent produced by WH exhibited excellent magnetic characteristics and remarkable adsorption properties for methylene blue (MB) (524.20 mg g^{-1}), methyl orange (425.15 mg g^{-1}), and tetracycline (294.24 mg g^{-1}) adsorption (Saning et al., 2019). This outstanding efficiency is attributable to the magnetic carbon composite's high specific surface area with significant mesoporosity (Sarkar and Dey, 2021). In another instance, the primary benefit of an adsorbent composed of WH, powdered and granular activated carbon was observed as being more accessible to regeneration beyond the considerable loss of adsorption performance for para chloro meta xylenol following continuous application of up to three cycles (Sharma et al., 2021). Besides its greater reusability, magnetite was included in the WH adsorbent as an enhancer to remove petroleum oil spill contaminants from contamination (Shokry et al., 2020). The scientists could decontaminate crude oil contamination by utilising oil spill collectors to absorb the heavier particles using an external magnet.

The modification of WH to biochar has been shown to modify the adsorbent's surface (Hashem et al., 2020; Liu et al., 2020; Xu et al., 2020; Zhou et al., 2020), revealing the material's distinct properties. Carbonization of WH has been shown to boost the aromaticity and carbon stability of the biowaste (Gaurav et al., 2020; Sun et al., 2021). Nonetheless, the biochar contains hydroxyl and carbonyl functional groups (Sun et al., 2021). This suggests that the biochar remains capable of adsorbing organic contaminants from the water column. This has been established by the ability of WH biochar with Fe_3O_4 support to remove glucose and 2, 4, and 6-trichlorophenol (Zhang et al., 2018). However, adsorption studies in this area remain restricted because of the additional step necessary to prepare biochar.

3.2.3. Adsorption mechanism for organic contaminants removal

Likewise, other adsorption techniques used to remove organic contaminants in wastewater govern effective adsorption by various parameters, particularly pH, contact time, initial adsorbate concentration, and adsorbent mass (Amalina et al., 2022). According to kinetic modelling, the pseudo-second-order model mainly corresponds to chemisorption is dominant through the adsorption of organic contaminants over WH-based adsorbents (Khanh et al., 2020; Lima et al., 2020; Liu et al., 2018; Madikizela et al., 2018). In several investigations, electrostatic interactions were ascribed to the adsorption of organic toxins (Khanh et al., 2020). Consequently, naproxen adsorption on activated carbon from the WH stem was maximized at pH 10 due to the deprotonation of the adsorbate, which results in its being negatively charged (Khanh et al., 2020). Meanwhile, another situation was given separately, with ibuprofen adsorption found to be effective on magnetic hybrid material synthesized with WH at a pH 3 (Jaroniec et al., 2020). This has been ascribed to hydrogen bonds among the protonated carboxylic groups of ibuprofens and the protonated hydroxyl and carboxylate groups of the adsorbent and strong π–π and hydrophobic relations, given that ibuprofen is hydrophobic at pH 3 (Lima et al., 2020). Phenol elimination employing WH ash is more efficient at lower pH values (Talaiekhozani et al., 2021).

Numerous theories exist regarding which isotherm best explains the adsorption mechanism. This indicates that the adsorption mechanism is adsorbate specific. The Langmuir, Freundlich, and Redlich-Peterson isotherms shown being the best fits for organic adsorption (Amalina et al., 2022; Liu et al., 2018; Talaiekhozani et al., 2021). The Freundlich isotherm was converted into the adsorbate's multilayer coverage on a heterogeneous surface (Liu et al., 2018). The Langmuir isotherm is used to characterize monolayer coverage.

It was evident from the data provided in this section that the adsorption process for organics is not well comprehended. This is corroborated by the article performed on the chemical activation of naproxen on activated carbon from WH stems (Wahi et al., 2017). The adsorption of naproxen has been hypothesised to π–π and electrostatic interactions mediated by the surface chemistry formed by the oxygenated groups on the adsorbent surface and the aromatic rings in the activated carbon's graphic structure (Mishra et al., 2021).

3.3. Dye removal from water

3.3.1. Dyes in water

Dyes are chemicals applied to colour a wide range of products, including textile, paper, leather, petroleum, and foodstuff

(Islam and Mostafa, 2019). Dyes have been found to infiltrate aquatic systems significantly, primarily from industrial wastes (Gu, 2021). Their concentrations in the environment, though, are lowered due to dilution and dispersal over the diverse layers of the atmosphere. These dyes are classified as micropollutants or emerging toxins since they occur at low concentrations in the aquatic system and have a detrimental influence on human health and the environment (Ahmed et al., 2020). Diverse colours have been identified in numerous water samples (Jesudoss et al., 2020; Zhou et al., 2020). Issues about dyes in the aquatic system develop due to their adverse health impacts (Nedjai et al., 2021). Once consumed, dyes typically comprise carcinogenic amines, metals, pentachlorophenol, chlorine bleaching, halogen carriers, free formaldehyde, biocides, fire retardants, and softeners (Benkhaya et al., 2020). Until now, substantial research has been performed upon adsorptive removal of dyes in water using WH (Samsami et al., 2020; Sarkar and Dey, 2021).

3.3.2. Dye adsorption chronological

Since the 1990′s, plant roots have been capable of removing MB and Victoria blue dyes from water, with adsorption rates of 128.9 and 145.4 mg g^{-1} (Madikizela, 2021). Contrasted with other aquatic macrophytes like Pistia stratiotes, Lemna minor, and Salvinia sp., WH has been proven to remove various textile pollutants from water (Nyoo et al., 2021). WH roots for the sorption process were a successful conceptual model that could be integrated into phytoremediation, as the roots are the only parts submerged in natural water sources (Haziq et al., 2020). It has been stated that plants absorb pollutants and transmit them to aerial sections of WH (Mlunguza et al., 2020). Proportionately, those plant segments (roots, stems, and leaves) were investigated for their ability to adsorb water contaminants such as dyes (Herrera-González et al., 2019; Kadhom et al., 2020; Wu et al., 2019; Yaashikaa et al., 2020; Zhou et al., 2019). Henceforth, the entire plant has been employed to adsorb dye in water without subdivided segments (Awe et al., 2020; Hassan and Carr, 2021; Rangabhashiyam and Balasubramanian, 2019). This may decrease adsorption capacity and a slowing of the uptake process in circumstances when another plant segments are preferable as biosorbents. It is well established in the article that particular plant segments may more efficiently absorb dyes than others (Saufi et al., 2020). For instance, the highest adsorptive rates of Rhodamine B were estimated to be 27.15 mg g^{-1} when the roots and leaves of WH were utilised (Saufi et al., 2020). In a separate context, roots were observed to absorb MB rapidly than leaves and stems (99% in less than 5 min) (Kadhom et al., 2020). Nonetheless, adsorption with a whole plant minimises the possibility of toxic products once unwanted plant segments are discarded.

According to Table 2, WH has been examined for its ability to remove many dyes from water. As shown in Table 2, the adsorption rate is highly dependent on the adsorbent composition. Chemically treated adsorbents demonstrated increased adsorption strengths (Babiker Daffalla et al., 2020). Throughout this scenario, surface modified WH (modified with N-Cetyl –N,N,N–trimethyl ammonium bromide) extensively absorbed Remazol Brilliant Red 3BS dye from aqueous solutions, achieving an adsorption rate of 104.26 mg g^{-1}, approximately tenfold that of activated carbon (Ranasinghe et al., 2019). Chemical treatment influences the physicochemical properties of WH by providing functional groups that facilitate the dye's adsorption, primarily increasing the adsorbent's surface area (Conte et al., 2021; El-naggar et al., 2019; Sizmur et al., 2017). This increases the binding capacity. Citric acid was used in one investigation to convert the hydroxyl groups in WH cellulose into esters. This culminated in much greater removal efficacy for reactive blue and crystal violet dyes compared using unmodified WH for adsorption (Ma et al., 2021). Correspondingly, adding carboxyl groups to biochar synthesized from WH via the esterification process enhanced the adsorbent's ability to remove MB dye in water (Biomass et al., 2021). In another experiment, functionalizing WH with zinc oxide nanoparticles and coating it with polyethyleneimine increased the surface area of the adsorbent between 133 and 152 m^2 g^{-1}, succeeding in higher efficiency with respect to the adsorbent in its original state (Li et al., 2019).

3.3.3. Adsorption process parameters

Numerous variables affecting the adsorption behaviour have been identified, including pH, initial concentration, contact time, and temperature (Amalina et al., 2022). Although the effect of temperature is frequently neglected (and hence excluded from Table 2), some studies have suggested that it is critical for dye adsorption while using WH (Conte et al., 2021; El-naggar et al., 2019; Sizmur et al., 2017). Nevertheless, recent analyses have proved that dye's adsorption by WH is temperature independent (Ha and Lee, 2020). Previously, it was discovered that the percentage of dye removed decreased as rising temperature (Conte et al., 2021; El-naggar et al., 2019; Sizmur et al., 2017). The main description offered in the report for such data is that as the dye molecules' total energy increases with temperature, the sorption capacity becomes less efficient (Hadzirun Muhamad Zubir et al., 2020). Meanwhile, other experiments have provided contradicting findings, demonstrating that increasing the temperature favours adsorption (Yaashikaa et al., 2020). The researchers concluded that increasing the temperature enhances the mobility of the massive dye ions in this situation (Bartolotta and Calogero, 2019). This suggests that the influence of temperature on dye adsorption employing WH must be explored in all future investigations to understand its role better. Along with its effect on the adsorption performance, the temperature is critical in understanding the kind of adsorption. In this scenario, thermodynamic analysis can be used to estimate if the adsorption mechanism was endothermic or exothermic (Runtti, 2016).

Countless investigations have established that the pH of the solvent is critical for the adsorption mechanism (Amalina et al., 2022; Conte et al., 2021; El-naggar et al., 2019; Sizmur et al., 2017). As illustrated in Table 2, the optimal pH level for dye sorption varies greatly. That is to be considered, as changes in pH affect both the adsorbate and the adsorbent's structural properties. This is frequently the determining factor in adsorption behaviour (Rashid et al., 2019). An appropriate example is given elsewhere (Nyoo et al., 2021). Researchers encountered maximal adsorption of amaranth dye at low pH due to protonation of WH leaves, which resulted in electrostatic attraction between the positively charged and the anionic adsorbate compounds. Additionally the increased adsorption rate of Indosol Dark-blue GL dye between pH 2 and 5 was ascribed to the electrostatic attraction over the positively charged adsorbent surface and the anionic dye (Lai et al., 2020). As a result, the solution pH remains a critical parameter to optimise during dye adsorption onto the WH.

The intensity of the adsorption process is determined by both the dye concentration and the contact time. Increased dye solution concentration enhances the accessibility of dye molecules at the adsorbent interface, increasing adsorption performance (Lai et al., 2020). After that, when dye molecules cover the active sites on the adsorbent surface, the removal efficiency reaches a maximum, resulting in saturation adsorption (Meko, 2021; Ying et al., 2021). Contact time is critical since it dictates the duration required to reach equilibrium. This is regulated by the mass transfer rate, which determines the contact conditions among the solid and liquid phases (Zhang et al., 2020).

3.3.4. Dye adsorption mechanism

According to Table 2, pH is essential for dye adsorption into WH biomass. Since structural changes on both the adsorbent's surface and the adsorbate's molecular structure do occur, the electrostatic attractions were identified as the primary determinant of the adsorption system (Fig. 3) (Amalina et al., 2022; Bartolotta and Calogero, 2019; Chen et al., 2019; Salahuddin et al., 2021; Sarkar and Dey, 2021). For instance, when WH roots were used as the adsorbent, four dyes (MB, Congo red, crystal violet, and MG) were removed more effectively at relative pH values (pH 7–9) (Gaurav et al., 2020). This was

Table 2
Efficiency of WH-based adsorbents for organic dyes removal.

Adsorbent (g L^{-1})	Dye	Operating parameters				Adsorption isotherm and kinetics	Refs.
		Initial concentration (mg L^{-1})	pH	Contact time (min)	Max. adsorption performance (mg g^{-1})		
Roots	Indosol Dark-blue GL	–	3	–	86	Langmuir	Lai et al. (2020)
Roots (1)	Congo red	–	6	180	46	Redlich–Peterson second order	Gaurav et al. (2020)
Roots	BF — 4B red reactive dye	–	2	110	43	Elovich, Pseudo-second order	Kadhom et al. (2020)
Roots treated with hydrochloric acid (1.5)	Dark blue-GL	150	3	110	60	Langmuir, Pseudo-second order	Salahuddin et al. (2021)
Roots and Leaves (1)	Rhodamine B	–	3–12	120	27 45	Langmuir, Pseudo-second order	Saufi et al. (2020)
Phosphoric acid-treated stem (0.6)	Cotton Red B2G, Cotton Blue B2G, Cotton Yellow 2RFL	>30	–	60	99% efficiency	Langmuir, Pseudo-second order	Madikizela (2021)
12% aminated raw stem with sandene (10)	Two azo and four anthraquinone anionic dyes	100	3	10	–	Freundlich, Pseudo-first order	Sharma et al. (2021)
Roots (1.5)	Crystal violet	100	7.8	120	323	Langmuir, Pseudo-second order	Gaurav et al. (2020)
Carbonized whole plant (1)	Crystal violet	20	8	TD	58.13	Langmuir, Pseudo-second order	Ma et al. (2021)
Leaves (1)	Amaranth dye	200	2	420	70	Langmuir, Pseudo-second order	Nyoo et al. (2021)
Cellulose-based water hyacinth, functionalized with chitosan and TiO_2 nanoparticles	Reactive Black 5	–	2.5–3	60	0.606	Langmuir, Pseudo-second order	Lai et al. (2020)
Whole plant chemical modified with citric acid (1 g/40 mL)	Reactive Blue 21 and crystal violet	15	<7	120	–	Langmuir, Pseudo-second order	Emam et al. (2020) Ma et al. (2021)
Citric acid-modified biochar derived stems	MB	–	10	60	395	Langmuir, Pseudo-second order	Conte et al. (2021)
Nitric acid-treated leaves and stems (2)	MB	286	–	–	–	Pseudo-second-order	Kadhom et al. (2020)
Roots, stems and leaves	MB	–	2–14	20	35	Freundlich, Pseudo-second order	Bedia et al. (2018)
Whole plant (30)	MB	781 mM	–	–	246 mM g^{-1}	Pseudo-second-order	Saufi et al. (2020)
Whole plant (5)	Methyl red	250	8	180	8.8×10^{-2} mol	Langmuir	Roik et al. (2021)
Whole plant charcoal modified with cationic surfactant (1)	Congo red	–	2	120	103	Langmuir, Pseudo-second order	Munagapati et al. (2018)
Roots (1.5)	Congo red	–	–	90	–	Freundlich, Pseudo-Langmuir	Biomass et al. (2021)
Roots fixed on calcium alginate (8%)	MB crystal violet	–	8–10	–	111 44		Salahuddin et al. (2021)
Water hyacinth (6.5, 7.5, 6.0, and 7.0)	MB, Congo red, crystal violet, and malachite green (MG)	65, 75, 70, and 75	7.0, 6.0, 8.0, and 8.0	7200 (5 days)	148, 149, 150,	Langmuir, Pseudo-second order	Senthil and Lee (2020)
Magnetic porous carbon materials from stems	MB and Methyl orange	–	–	–	300	Langmuir, pseudo-second order	Saning et al. (2019)

justified because of an increment in pH resulting in a significant rise in dye-binding capacity because of the strong electrostatic attraction of negatively charged biosorbent sites and dye cations. Additionally, it was discovered that WH roots predominantly contain —PO_4, C=O, and C—H functional groups on the surfaces. All of the dyes examined are cationic charges, forming in an aqueous medium as positively charged ions (Gaurav et al., 2020).

The kinetic model was mainly well-fitting. A pseudo-second-order model indicates the presence of chemisorption (Amalina et al., 2022; Bartolotta and Calogero, 2019; Chen et al., 2019; Salahuddin et al., 2021; Sarkar and Dey, 2021). Thus, physisorption was the most appropriate way to define the adsorption of methyl red (Roik et al., 2021).

Based on Table 2, the Langmuir isotherm is considered superlative vital for dye adsorption on WH. This isotherm signifies that the dye forms a monolayer on the adsorbent's outer surface; consequently, since an adsorbate molecule occupies an adsorption site, no additional desorption may occur within the same site (Bhattacharjee et al., 2020). Simultaneously, this indicates that dyes are adsorbed at specified homogenous sites inside the adsorbent, in which entirely sorption sites are similar

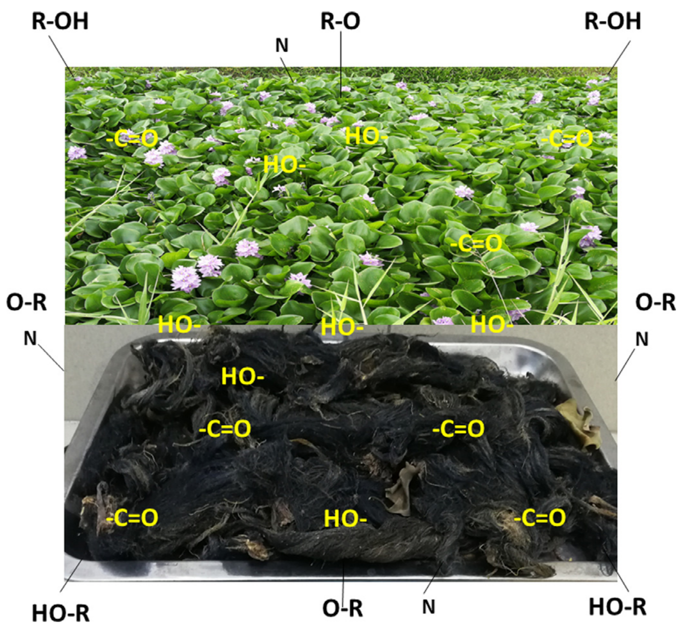

Fig. 3. The prevalent mechanism of organics adsorption into WH-based adsorbents.

and energetically equal (Bhattacharjee et al., 2020). Several exclusions were disclosed for MB, and Congo red dyes and the isotherm data fit the Freundlich model well (Bedia et al., 2018). Adsorption began on a heterogeneous surface, in this instance, via a multilayer adsorption process (Bedia et al., 2018).

Crystal violet adsorption onto low-cost carbon synthesised by WH was spontaneous and endothermic (Munagapati et al., 2018). Analogously, (Senthil and Lee, 2020) demonstrated the adsorption of cationic dyes (MG and MB) on WH roots. Notwithstanding, for Rhodamine B, spontaneous and exothermic adsorption was observed (Saufi et al., 2020). Exothermic reactions were also used to describe the adsorption of MB (Leng et al., 2021).

By summarising the adsorption process of various dyes on adsorbents derived from a WH, each adsorbate has a unique tool. Different dyes in solvents exhibit physical, chemical, and molecular properties.

4. Insights into future research

Several researchers have described the potential to reuse WH adsorbents multiple times following adsorbent regeneration (Li et al., 2021; Lima et al., 2020). The above implies that aqueous resources can still be remedied even during the seasons when the WH is scarce or unavailable. Additionally, encouraging research has been performed, indicating that WH can be reused for plant uptake (Yaashikaa et al., 2020). Moreover, additional study is needed, as this was only published for the uptake of formaldehyde by plants, demonstrating the reusability at least four times (Talaiekhozani et al., 2021).

According to a few experiments, WH roots may absorb organics through polluted water and then translocate them to aerial tissues (stems and leaves) (Mlunguza et al., 2020; Shokry et al., 2020; Yamkelani Mlunguza et al., 2020). Nevertheless, data regarding uptake rates, maximal concentration, and organics that WH can absorb are still scarce. The whole range of substances that the WH roots can absorb must be studied. As a result, additional plant uptake experiments using hydroponic systems are obligated. Toward a larger scale, the feasibility of employing constructed wetland systems as a supplementary purification approach in water treatment plants with living WH capable of organics uptake should be explored.

This review emphasised the possibility of converting WH, an invasive species, into value-added products. Activated carbon derived from WH has been demonstrated to reduce water pollution by removing naproxen (Nidheesh et al., 2021). Moreover, additional research is required to optimise the experimental procedures for optimum adsorbent performance. Future research is needed to demonstrate the potential application of WH-based adsorbents for the simultaneous adsorption of a diverse array of emerging contaminants.

According to data under this overview, WH can successfully remove dyes and other organic substances from water. Thru hydrogen bonding and electrostatic interactions, WH acquires functional groups, usually carboxyl, hydroxyl, and carbonyl, that encourage the adsorptive rate of water effluents. Furthermore, π-π interactions aid in the elimination of organic contaminants. This implies that WH adsorbents can remove a broad spectrum of emerging pollutants in wastewater. As described in this assessment, these toxic compounds include a variety of organic chemical classes, including pharmaceuticals, herbicides, and polycyclic aromatic hydrocarbons. Regrettably, additional studies are necessary to exploit the potential of WH-based adsorbents by adapting them to the simultaneous adsorption of a diverse spectrum of organic substances instead of limiting the exploration to several compounds. This is feasible since WH has a low specificity.

5. Conclusions

This paper attempts to give a complete assessment of the applications of WH for watercourses treatment. These are intriguing applications aimed at repurposing the inconvenience presented by invasive species to address the scarcity of clean water. This article demonstrates that both naturally occurring and chemically engineered forms of WH can be critical in water purification. The native conditions of the WH as adsorbents are of importance since there is no demand for any specific equipment, operation, power, or chemicals in the purification process. Interestingly, it has been demonstrated in the literature that WH may absorb organic substances from polluted water, which is an intriguing feature of this invasive macrophyte in water. Numerous studies have indicated that solution pH plays a crucial role in adsorption. As described above, the optimum pH values for the adsorption of different dyes vary significantly. This is expected as the change in pH alters the chemical structure of both the adsorbate and the adsorbent. This often determines the adsorption mechanism. Meanwhile, the contact time was identified as the optimum parameter for removing antibiotics from polluted waters. Given that WH also threatens aquatic life's survival, a study is essential to find a compromise between water remediation and marine species' health. This is crucial because the use of WH for water body rehabilitation is seen as a realistic alternative for countries or areas facing financial difficulties. The advantageous addition of WH waste in the manufacturing of eco-friendly biochar is used as an alternative for solving strategy for solid waste management, and further, it helps in the removal of the organic contaminants. Research is not sufficient in controlling WH. Considerable research is still needed to control invasive plants by adapting new ways such as the conversion of biomass into biochar for soil remediation, used as catalyst materials, carbon sequestration process, and enhanced production method.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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